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Endogenizing the probability of nuclear exit in an optimal power-generation mix model

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ABSTRACT

A major accident at a nuclear power reactor can lower public acceptance of this energy source and may result in a nuclear exit. This paper proposes an optimal power-generation planning model that deals explicitly with the costs involved in changing the power-generation mix due to a nuclear exit. The model introduces the probability of a major accident leading to a nuclear exit at a future time period as an endogenous variable, which is determined depending on the amount of nuclear power being generated during the preceding period. The proposed model is formulated as a stochastic programming problem that aims to minimize the expected value of overall power-generation costs computed with a weighted probability of every future state, branched according to a possible nuclear exit at each time period. An application of the model quantitatively implies that less nuclear dependency is optimal for a higher assumed frequency of a major accident per generated unit of electrical energy from nuclear—not only for the cost of direct damage from the accident, but largely because of the increased cost of overall power generation due to the subsequent nuclear exit. To put it differently, lowering the frequency of a major nuclear accident per reactor·year brings benefits exceeding the conventionally perceived effect of reducing an accident's direct damage. Lowering the major accident frequency to one per 10^6 reactor·years would free the optimal planning of future electricity supply from influence of an accident causing nuclear exit, if the geographical scale of the exit were limited to one-twentieth of the entire world.

1. Introduction

Nuclear power generation is acknowledged to be cost-effective and to involve lower life-cycle emissions of greenhouse gases than mainstream thermal power generation options. A literature survey has shown that the life-cycle emissions of greenhouse gases per unit of generated electrical energy from nuclear power generation are estimated to be lower than those from conventional coal-fired power generation by two orders of magnitude [1]. A specific evaluation study on the life-cycle emissions of carbon dioxide (CO_2) of Japanese light-water and fast breeder reactors concluded that the expansion of nuclear power generation is effective to reduce CO_2 emissions in the power sector [2]. Accordingly, some expect future increases of nuclear power generation in the effort to cope with the global need to mitigate the depletion of fossil fuel resources and the progress of climate change [3]. Nevertheless, the probability of a major accident occurring at a nuclear power reactor can never be completely nil.

A major nuclear accident with radioactive contamination causes two types of economic and environmental losses: the first is direct damage to those residing near the reactor, including health impacts and relocation costs, which are generally regarded as the impact of a nuclear disaster; the second type of loss involves the increase in the overall cost of the power supply, together with the cost of intensified emission of CO_2, due to the increased operation of fossil-fired power plants when operation of the nuclear reactor is suspended, even if temporarily, after the accident. Such nuclear suspensions can be prolonged, and may even evolve into a phase-out or permanent exit, depending on the tenor of public opinion. In fact, the 2011 Fukushima Daiichi nuclear

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accident inflicted the second type of loss on Japan as seriously as the first.[1] Moreover its effect has crossed international borders. For instance, as a result of the Fukushima accident, the German government decided to accelerate its abandonment of nuclear power generation [6].

There is a wide range of views regarding how much a major nuclear accident intensifies social pressure in favor of nuclear phase-out or exit. Siegrist et al. showed that the impact of the Fukushima accident on public opinion was limited [7]; Hayashi and Hughes indicated a similar result and argued that a fundamental shift in global nuclear generation policy resulting from the accident is quite unlikely [8]. A statistical analysis by Csereklyei regarding the impacts of the past two serious accidents at Three Mile Island in 1979 and Chernobyl in 1986 on the downward trend of nuclear plant installation revealed that the impact of the former accident was limited only to the United States while the latter accident had a global influence [9]. Joskow and Parsons, who formerly stated that "another significant accident at an existing nuclear plant anywhere in the world could have very negative consequences for any hope of a nuclear renaissance" [10], have claimed that the Fukushima accident would contribute to a reduction in the future nuclear expansion trend; however, this contribution has turned out to be very modest at the global level [11]. Pedraza expressed an extreme view that "if a new nuclear accident occur [sic] in the future in any nuclear power plant, then the use of nuclear energy for the generation of electricity will be excluded from the energy mix of all countries" after the Fukushima accident [12].

While it is uncertain how another major accident in the future would influence the use of nuclear energy in the power sector, the possibility of causing the above-mentioned second type of loss cannot be excluded. Were a nuclear phase-out or exit to occur after nuclear dependency has developed, our society would suffer a surge in electricity costs and increased CO_2 emissions; this is not favorable from a view point of sustainable development, especially if those impacts occur on a large scale. Given the public-goods characteristics of electricity and CO_2, it is important to examine the impact of the second type of loss potentially caused by another major accident on the desirable future evolution of the power-generation mix from a precautionary point of view. This examination would also help elucidate the effect of lowering the frequency of accidents per unit of generated energy by enhancing the safety of nuclear reactors to alleviate not only the first but also the second type of loss.

With this background in mind, this paper proposes a mathematical programming model with which to derive the optimal intertemporal path to a power-generation mix taking both types of losses into account, and presents an application of the model under tentative assumptions. Existing studies have evaluated each type of loss independently, as shown in the following review section. However, to the best of our knowledge, no study has attempted to demonstrate a cost-optimal power-generation model that considers an integration of the two.

[1] The accident at the Fukushima Daiichi nuclear plant triggered the suspension of almost all nuclear power stations for several years in Japan, leading to an increase in the overall electric-power supply cost. The cumulative cost increase over the four years up to the end of 2014 fiscal year was estimated to be 12.7 trillion JPY (Japanese yen), approximately 110 billion USD (United States dollars), according to the Agency for Natural Resources and Energy [4].

As for the direct damage cost due to the accident, admitting the great difficulty of its estimation, compensation for damages paid by the Tokyo Electric Power Company to victims evacuated from their homes in the area surrounding the nuclear plant may give a reference value. As of 27 November 2015, the cumulative total amount of compensation was 5.73 trillion JPY, equivalent to approximately 50 billion USD [5].

The proposed model deals stochastically with a sudden nuclear exit in response to a major nuclear accident that potentially occurs at any time in the future. The probability of an accidental nuclear exit at each time period is introduced as an endogenous variable associated with nuclear power generation in the preceding period. It derives the future power-generation mix so as to minimize the discounted sum of the expected value of overall power-generation costs, calculated by weighting with the endogenized probability of a nuclear exit at each time period.

The remainder of the paper is structured as follows. Section 2 reviews past studies regarding power-generation planning that took the impacts of major nuclear accidents into account, and clarifies the difference between them and the present study. Section 3 introduces the formulation of the optimal power-generation mix model that endogenizes the probability of a nuclear exit proposed in this study. In Section 4, the assumptions and results of the first demonstration of the model are described. The results computed with the proposed model will be contrasted with those of a conventional model that does not consider a nuclear exit. Section 5 presents a selected sensitivity analysis that assumes variations of the crucial parameter settings. Finally, Section 6 summarizes the outcome and concludes by addressing the limitations of the study.

2. Brief literature review

The EC (European Commission) estimated the costs of direct damages caused by a major nuclear accident and associated radioactive contamination as a part of its ExternE project, aimed at assessing the external costs of energy [13]. It calculated the expected value of the nuclear accident-associated external cost per generated unit of electrical energy as the product of the estimated damage cost and the frequency of an accident per unit of generated nuclear energy.

Since the ExternE project was conducted as a pioneering work, many have attempted to assess the external cost of nuclear power generation and nuclear accidents. Recent examples include the following: Sheldon et al. evaluated the life-cycle environmental externalities of hydro and nuclear power plants including potential accidents in terms of replacement energy inputs [14]; Sovacool et al. assessed the property damage and human fatalities caused by accidents in each of 11 energy systems including nuclear power generation based on a statistical analysis of past accident cases [15]; Silva et al. estimated the cost per severe nuclear accident applying the methodology of probabilistic risk assessment [16]; and Rabl and Rabl showed that the cost of a major nuclear accident could be one order of magnitude greater than the estimates of the ExternE project as the accident-oriented displaced population might be very large depending on the nuclear reactor site [17]. Hughes has attempted to deal with the rather indirect impacts of an accident [18]. He provided a framework with which to evaluate the impact of various events and their durations on the resilience and adaptation of energy systems, though he has as yet presented no quantitative evaluation of a nuclear accident.

Some energy modeling studies have assessed the cost-optimal energy supply system structure taking the above external costs into account. A typical example is a study by Rafaj and Kypreos [19], which added the external costs of accidents, air pollution, climate change, and other burdens to the ordinary private costs of various power-generation options in their MARKAL-type global energy system model to derive the power generation mix that minimizes the sum of private and external costs. Similar studies include the following: de-Llano Paz et al. took into account the external costs in an electricity best-mix model based on the portfolio theory considering the variability of technology costs [20]; Kosugi et al. internalized the monetary values of several environmental loads calculated based on a Japanese life-cycle impact assessment as the external costs in an integrated assessment model [21]; Zheng et al. added the external costs of the CO_2, nitrogen oxides, and sulfur oxides emissions in a cost-minimization model of the electric power generation and transmission system for China [22]; and Yuan et al. introduced nonlinear external costs in an energy systems model [23]. Hong et al. showed that utilizing nuclear power is the most sustainable option by comparing among power supply scenarios taking into account the external costs including the cost of damage due to accidents, though the evaluation excluded indirect impacts caused by a potential nuclear phase-out or exit after the accident [24]. An interesting recent study by Seddighi and Ahmadi-Javid modeled the expansion planning of power generation and transmission considering that a large earthquake causes drops in the power generation and transmission capacities at certain rates [25]. However, this series of studies did not consider the possibility that nuclear power will be phased out after an accident.

On the other hand, many studies have evaluated the impact of a nuclear phase-out or exit on the economy and on CO_2 emissions. A scenario of global nuclear phase-out, i.e., no installation of any new capacity of nuclear power generation, was examined by Rogner and Riahi with an integrated assessment model [26]. Similarly, Duscha et al. assessed the costs of meeting international CO_2 emission targets for 2020 under a global nuclear phase-out scenario with an energy systems model and showed a substantial variation in the impact of the phase-out among countries [27]. In addition to a phase-out scenario, a full-exit scenario in which no new plant installation is allowed and all the existing plants are decommissioned was considered by Bauer et al. using an inter-temporal general equilibrium model [28]. They showed that, while such a nuclear exit could cause a larger negative economic impact than the phase-out, this impact would be outweighed by the impact of a stringent CO_2 mitigation policy.

Existing country-level studies include the following: the impact of a nuclear phase-out for Japan was estimated by Nakata with an energy-economy model [29]; Su et al. considered a scenario of zero nuclear power generation in Japan by 2030 with their model [30]; and Zhang et al. evaluated both a nuclear phase-out and exit scenarios for Japan using a multi-objective optimization model taking economic and environmental efficiencies into consideration [31]. Studies assessing the impact of a nuclear phase-out also exist for the United States [32], Germany [33], and Switzerland [34].

In general, these studies consider exogenous scenarios of phasing out nuclear power using energy-economy models, and they show that a nuclear phase-out leads to an increase in the overall cost of the energy supply and related CO_2 emissions to a greater or lesser extent.[2]

The above set of studies, however, provides no answer to the question regarding the globally or regionally desirable power supply structure including nuclear options in the future under the possibility of nuclear phase-out or exit. The present study tackles this question. Again, our objective here is to design and demonstrate a mathematical model capable of reflecting the impacts of the direct damage of a major nuclear accident and of the anticipated nuclear suspension after the accident on optimal power-generation planning. Details of the model and its application are described below.

[2] De Cian et al. [35] applied a similar approach to consider a nuclear phase-out scenario in their integrated model of energy, climate and economy. However, their results are different from the other past studies as their model deals with the research and development (R&D) of energy technologies endogenously. They estimated that, while the power supply cost increases in the short term after a nuclear phase-out, it would be offset in the long run by the benefits of accelerated R&D of inexpensive power generation technologies stimulated by the phase-out.

3. Mathematical modeling of optimal power-generation mix

3.1. Conventional modeling: 'No nuclear exit after accident' case

An optimal power-generation mix model is in general designed to derive the least-cost intertemporal path to a combination of power-generation options, typically including coal- and gas-fired, hydro, biomass, wind, solar, and nuclear [36]. In such a model, the power capacity and amount of generated power of each option at each time period are treated as major endogenous variables, which are associated with other variables representing fuel consumption, CO_2 emissions, power generation cost, etc. The model is formulated as a mathematical programming problem to compute optimal solutions of those endogenous variables so as to minimize the objective function of the overall power-generation cost, summed up over the evaluation time periods, and subject to some technical and environmental constraints. Outside of a few exceptional time-independent variables, each variable is expressed as a time series vector like $X(t)$, where t represents a time period.

A conventional way of taking the externalities of power generation into account in the model is, as described in the previous section, to add the expected value of the external cost on to the objective function. This assumes no probability of nuclear exit in response to a nuclear accident. It thus eliminates the likely increase in overall power-generation cost caused by the replacement of nuclear with other, more expensive options due to an accidental nuclear exit. Hereafter, we refer to cases that apply this conventional model as 'No nuclear exit after accident' cases.

Among the various kinds of externalities, we now focus specifically on the damage costs of a major nuclear accident as the externality relevant to the purpose of the study. Other externalities are not taken into account to simplify the discussion; in addition, the external costs of minor nuclear accidents/incidents are not considered. Let a time period cover ten years. The objective function in this case is the overall cost of power generation summed up from the initial to the final time period, and is expressed as follows:

$$COST_{\mathrm{conv}} = \sum_t \left[C_{\mathrm{p}}(t) + 10G(t)p_{\mathrm{ac}}D_{\mathrm{ac}}(t)\right]R(t), \tag{1}$$

where $C_{\mathrm{p}}(t)$ denotes the decadal overall power generation cost consisting of capacity installation costs, operation and maintenance costs, fuel costs, CO_2 capture and sequestration costs, power plant decommissioning costs, and nuclear back-end costs at time period t. $R(t)$ denotes the exogenously determined discount factor at time period t relative to the initial time period t_0. $R(t)$ is calculated with a constant annual discount rate ρ as follows:

$$R(t) = (1+\rho)^{-10(t-t_0)}. \tag{2}$$

The term $10G(t)p_{\mathrm{ac}}D_{\mathrm{ac}}(t)$ in Eq. (1) represents the expected value of the damage costs of a major nuclear accident. The factor p_{ac} is an exogenously assumed average constant frequency of a major accident occurrence per unit of electrical energy generated from a nuclear plant, while $D_{\mathrm{ac}}(t)$ is the damage cost of the accident assumed to be set at a constant value, δ_{ac}, regardless of time period. $G(t)$ is an endogenous variable representing the annual nuclear power generation at time period t. The multiplier 10 is simply used to convert an annual cost into a decadal cost.

The model includes the following constraints, similar to general conventional power-generation planning models: the supply-demand balance of electrical energy at each load time-slot; the limitation of generated power due to the capacity factor of power plants; the inability of hydro, wind and solar power generation options to conduct load-following operations; the limitation of solar power generation to higher load time slots in the daytime; the consistency of power capacity stock evolution with newly installed and decommissioned capacities; the sufficiency of total power-generation capacity excluding intermittent power-generation options, i.e., wind and solar, to match the peak power load plus reserve margin; the economic availability of hydropower and biomass resources; an 'inertia' in energy systems (i.e., avoidance of extreme change in newly installed capacity over time); and an environmental constraint to limit the cumulative net CO_2 emissions from fuel combustion in the power generation sector. The electric power energy demand is assumed to follow an exogenously given intertemporal path without considering its price elasticity.

3.2. Proposed modeling: 'Nuclear exit after accident' case

The proposed model deals stochastically with the occurrence or nonoccurrence of a major nuclear accident. Depending on whether a major accident occurs or not at a time period when nuclear power stations are operating, one of two possible states will emerge at the subsequent period, as shown in Fig. 1. Once an accident does occur, it is assumed that nuclear power generation will be suspended, so that no additional accidents can occur after that.[3] We hereafter refer to cases adopting the proposed model as 'Nuclear exit after accident' cases.

In the model, an endogenous variable is expressed with two time dimensions, like $X(t, t')$ instead of $X(t)$, assuming a major nuclear accident at time period t'. With this extension, the number of variables is increased by a factor of the total number of time periods in the model. However, for any $t' \geq t$ (i.e., before a nuclear exit), $X(t, t')$ is independent of t' and is set at the same value as when t' equals the final time period, denoted by T, as follows:

$$X(t,t') = X(t,T) \text{ for } t' \geq t. \tag{3}$$

By Eq. (3), the number of free variables is virtually halved.

We assume that, if a major nuclear accident occurs at time period $t = t'$, all nuclear power plants will be quickly forced to exit (i.e., shut down), and annually generated electrical energy, as well as the newly installed capacity of nuclear, will stay at zero permanently. In other words, the variables for nuclear power generation and newly installed capacity, denoted by $G(t,t')$ and $N(t,t')$, respectively, meet the constraints expressed by Eqs. (4) and (5).

$$G(t,t') = 0 \text{ for } t' < t, \tag{4}$$

$$N(t,t') = 0 \text{ for } t' < t. \tag{5}$$

It is a strong assumption to consider a complete and permanent exit after a major accident, but this simplifies the formulation and computation of this stochastic model as it excludes the possibility of accident reoccurrences. For annual power generation from nuclear at any time period t before a nuclear exit, on the other hand, the following constraint applies:

$$G(t,t') = G(t,T) \text{ for } t' \geq t, \tag{6}$$

in accordance with Eq. (3).

[3] This assumption implies that 'a major nuclear accident' in the present modeling context denotes a catastrophic accident that could lead to a nuclear exit over a very long period in the region evaluated. Such an accident would presumably accompany a core meltdown causing large-scale proliferation of radioactive substances and radioactive contamination outside the power station site, which would be rated 7 on the INES (International Nuclear and Radiological Event Scale), although the possibility of a nuclear exit triggered by an accident rated at a lower INES level might not completely be excluded.

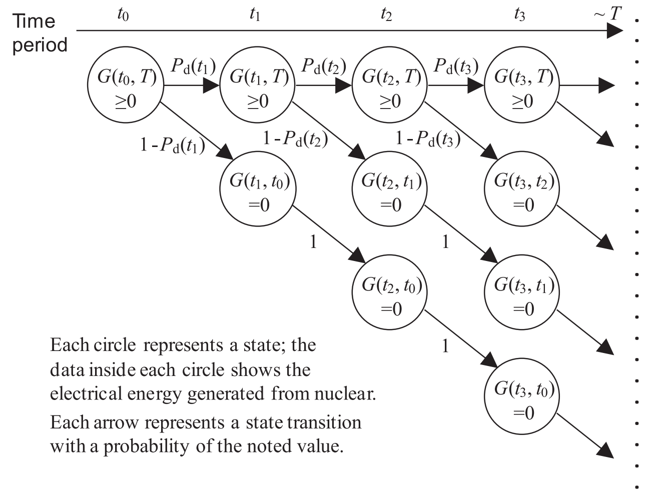

Fig. 1. State transitions with the passage of time in the proposed modeling, i.e., 'Nuclear exit after accident' cases.

Each state transition probability indicated in Fig. 1 is determined endogenously in the model, depending on the generated electrical energy from nuclear at the preceding time period, which is also an endogenous variable. Let us introduce an endogenous variable, denoted by $P_d(t+1)$, which represents the probability of transiting from time period t, at which nuclear power plants are in operation, to the period $t+1$ without an accident occurring in the decade. $P_d(t+1)$ is expressed as a function of the generated electrical energy from nuclear as follows:

$$P_d(t+1) = [1 - G(t,T)p_{ac}]^{10}, \tag{7}$$

noting that the annual probability of a nuclear accident at t before a nuclear exit is expressed as $G(t, T)p_{ac}$. Letting $P_c(t)$ and $P_n(t)$ denote the variables representing the cumulative probabilities of the occurrence and nonoccurrence of the nuclear accident from time period t_0 through t, respectively, the following formulas hold:

$$P_c(t+1) = P_n(t)[1 - P_d(t+1)], \tag{8}$$

$$P_n(t+1) = P_n(t)P_d(t+1), \tag{9}$$

with the initial conditions assumed as $P_c(t_0) = 0$ and $P_n(t_0) = 1$.

In the proposed nuclear exit after accident model, the objective function is defined as the probability-weighted dynamic overall power-generation cost, denoted by $COST_{exit}$, expressed as the product of the costs for all possible states and the probabilities of reaching the corresponding states as follows[4]:

[4] To supplement the derivation of Eq. (10), the probability-weighted decadal overall power-generation cost at the time period t is expressed as follows.

As seen in Fig. 1, the number of possible states at the time period t is t+1, letting t_0 be numerized as 0. The t+1 states consist of t states in each of which an accident occurs between each of the t-adjacent time periods, and one state in which an accident never occurs until the time period t.

The probability of reaching the state of an accident occurrence between the adjacent time period t' and $t'+1$ ($\leq t$) is $P_c(t'+1)$, and the decadal overall power-generation cost in the state is $C_p(t, t')$. The cost of an accident δ_{ac} is added to the power generation cost only for $t' = t-1$; i.e., when the accident occurs just before the time period t.

On the other hand, the probability of reaching the state of no accident occurrence by the time period t is $P_n(t)$, and the corresponding decadal overall power generation cost is $C_p(t, T)$.

From the above, the probability-weighted decadal overall power-generation cost at a certain time period t is expressed as $\sum_{t'=t_0}^{t-1}\{[C_p(t,t') + D_{ac}(t,t')]P_c(t'+1) + C_p(t,T)P_n(t)\}$ using the parameter $D_{ac}(t, t')$ defined by Eq. (11).

Table 1
Default settings for crucial parameters.

Item		Assumed value
Frequency of a major nuclear accident per generated unit of electrical energy from nuclear, p_{ac}		1×10^{-4}, 1×10^{-5}, 1×10^{-6} (reactor·year)$^{-1}$ or absolute zero
Reactor·year to TWh conversion factor		7.6 TWh/(reactor·year)
Damage cost of a major nuclear accident, δ_{ac}		150 billion USD
Cumulative CO_2 emissions limit in power generation sector		Zero accounted from 2010 to 2150
Annual electrical energy demand		
	Global (1:1 scale) model	Grow from 21.4 TkWh/year in 2010 to 130 TkWh/year in 2100
	Regional (1:20 scale) model	1/20th (= 5%) of the above
Annual discount rate, ρ		5%/year

$$COST_{\mathrm{exit}} = \sum_{t=t_0}^{T} \sum_{t'=t_0}^{t-1} \{[C_p(t,t') + D_{ac}(t,t')]P_c(t'+1) + C_p(t,T)P_n(t)\}R(t), \tag{10}$$

where $D_{ac}(t, t')$ denotes the damage costs caused directly by the accident and set at zero, except for a constant positive value assumed exogenously for $t = t' + 1$ as follows:

$$D_{ac}(t,t') = \begin{cases} \delta_{ac} & \text{for } t = t'+1, \\ 0 & \text{otherwise.} \end{cases} \tag{11}$$

In addition to Eqs. (3)–(11), all endogenous variables meet the constraints corresponding to those included in conventional models; constraints such as the supply-demand balance of electrical energy, and the upper limit on cumulative net CO_2 emissions must be satisfied even after a nuclear exit. The only exception is that the energy system's 'inertia' constraint regarding newly installed nuclear capacity is overwritten in the case of the nuclear exit, as indicated by Eq. (5). This approach follows the 'fail-safe' design we adopted in a previous climate-economy modeling [37].

External costs other than the damage costs of a major nuclear accident and the decommissioning costs for power plants other than nuclear are excluded in the present model as in the 'No nuclear exit after accident' cases.

4. Demonstration of the models

4.1. Assumptions

To demonstrate the conventional and proposed models, we developed a global model that treated the whole world as a single region. A model that covered a hypothetical region 1/20th the size of the entire world was also considered. We hereafter refer to the former and latter models as the Global (1:1 scale) and the Regional (1:20 scale) models. These two were assumed to compare the results for different regional coverage affected by a nuclear exit caused by an accident in the 'Nuclear exit after accident' cases.

The evaluation time range was assumed to be from 2010 through 2100; however, the final time period was set at 2150 for the purposes of the calculation to avoid a so-called termination effect (i.e., new capital investments would shrink as time approached the evaluation time horizon if we paid no attention to the economic activity after that period). Accordingly, the models cover fifteen 10-year time periods.

Table 1 shows some parameters considered crucial in the demonstration, and their assumed default value settings, the values of which should be given exogenously.

We assume three possible values with different orders of magnitude and zero for comparison as the frequency of a major accident leading to a nuclear exit per generated unit of electrical energy from nuclear, p_{ac}, considering its huge uncertainty. The

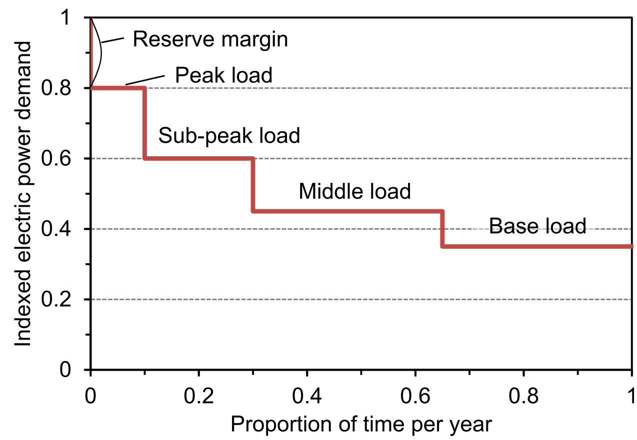

Fig. 2. Assumed annual electric power load-duration curve. The required total power generation capacity, including the reserve margin, is indexed as 1.

range of those value assumptions is supported by the following information: a nuclear accident's likelihood, presented by the Nuclear Regulatory Commission [38], includes the frequency of core melt as 1×10^{-4} per reactor·year and the frequency of containment failure as 1 in 100; multiplying these two frequencies yields 1×10^{-6} per reactor·year. The representative nuclear accident scenario shown in the ExternE project assumed a core-melt frequency of 5×10^{-5} (reactor·year)$^{-1}$ and a conditional frequency of a massive containment failure as 0.19 [13]. The frequency of a release from a core-melt accident with a massive containment release is thus assumed to be the product of the above two frequencies, i.e., $9.5 \times 10^{-6} \cong 1 \times 10^{-5}$ (reactor·year)$^{-1}$. More recently, the Electric Power Research Institute estimated the following average core-damage frequencies: 3.2×10^{-5} (reactor·year)$^{-1}$ for the year 2000, and 2.0×10^{-5} (reactor·year)$^{-1}$ for 2005 [39].[5]

The unit conversion factor from reactor·year to terawatt-hour (TWh) and the damage cost of a major nuclear accident are assumed based on the EC [13]. The latter figure corresponds to the largest monetary valuation, corresponding to the direct damage cost caused by a core-melt accident with a massive containment release, shown by the ExternE project. All monetary values are expressed in constant 2010 USD (United States dollars) in this paper.

We made tentative assumptions for the upper limit on the cumulative net CO_2 emissions from fuel combustion in the power generation sector and the annual discount rate, as shown in Table 1.

[5] It should be noted that there are more pessimistic estimates of the frequency of a major nuclear accident and the direct damage cost caused. Rabl and Rabl [17] advocate that, based on the historical record, the frequency of a major accident should be assumed to be one in 20 years per reactor, which is larger by two orders of magnitude than the highest assumed frequency in this study.

Table 2
Assumed characteristics and operational constraints for newly installed power-generation options.

Power-generation options	Capital cost (USD/W)	O&M cost (% of capital cost/year)	Decommissioning cost (% of capital cost)	Net thermal efficiency (%)[a]	Upper limit of capacity factor (%)	Suppliable load category	Plant lifetime (year)
Coal	1.36	3.7	5	44.8–53.0[b]	90	All	40
Coal-C. capt.	2.51–1.75[b]	4.2	5	36.8–48.4[b]	90	All	40
Gas	0.79	3.0	5	57.7–64.8[b]	90	All	40
Gas-C. capt	1.42–1.10[b]	3.0	5	49.7–60.5[b]	90	All	40
Oil	0.90	3.1	5	51.3–58.9[b]	90	All	40
Bio.	2.30–1.65[b]	3.5	5	35.0	70	All	30
Bio.-C. capt	3.60–2.12[b]	3.6	5	26.8–30.3[b]	70	All	30
Nuclear	3.49	3.2	15	–	85	All	40
Solar	2.95–0.33[b]	1.5	5	–	18	Peak & sub-peak	20
Wind	1.62–0.46[b]	1.5	5	–	25	Base	20
Other Re.	2.15–2.23[b]	2.5	5	–	35	Base	50

Note: 'C. capt.': CO_2 capture; 'Bio.': Biomass; 'Re.': Renewables (mainly hydro).
[a] Expressed on the basis of lower heating value.
[b] The left- and right-hand values correspond to those for power-generation options newly installed in 2010 and 2100, respectively.

Many studies of climate-economy integrated assessment modeling have implied the need for CO_2 emissions in the power generation sector to turn to negative by the end of this century to prevent anthropogenic CO_2 emissions from causing global average temperatures to rise more than 2 °C relative to pre-industrial levels [40]. Based on this, our demonstration limits cumulative CO_2 emissions accounted from 2010 to 2150 in the power generation sector to zero or lower. CO_2 emissions at each time period are determined endogenously in the model to satisfy the cumulative emissions limit.

The annual electrical energy demand is set exogenously at the actual value for 2010 [41]. Future demands are assumed based on the Current Policies Scenario, which appeared in the IEA's (International Energy Agency) WEO (World Energy Outlook) [42] up to the year 2030, and for the period from 2030 through 2100 on the A2 marker scenario of the IPCC's (Intergovernmental Panel on Climate Change) Emissions Scenario [43], which has been evaluated as the most realistic among the IPCC's scenarios [44]. The value for 2100 is also applied for the time periods after 2100.

The annual load duration curve is assumed to be four-stepwise, considering four demand categories of peak, sub-peak, middle, and base load, as shown in Fig. 2. The assumed annual load factor and the reserve margin rate are 60% and 20%, respectively, in keeping with the facts in major developed countries [45].

Table 2 summarizes the characteristics and constraints assumed for the newly installed power-generation options considered in the model. Most of the values are assumed according to the background data for the WEO [46]. The WEO reports the assumed investment costs and efficiencies of each power-generation option for nine world regions up to the year 2035. For our analysis, the universal costs and efficiencies are estimated as a weighted average applying the cumulative capacity additions by region and power source calculated in the same report. The assumed investment costs for the biomass-fired, CO_2-capturing power-generation options, solar, and wind options after 2040 are extrapolated from the decreasing trend from 2010 to 2035 assumed in the WEO. The costs are assumed to remain constant after 2100.[6] The net power-generation efficiencies of the coal, gas, oil, and biomass-fueled options up to the year 2100, including those with CO_2 capture, are also extrapolated from the assumed upward trend from 2010 to 2035 shown in the WEO.[7]

The plant decommissioning costs (percentage of the capital investment costs) are based on the default values assumed by the IEA and Nuclear Energy Agency [49]. The mass of nuclear fuel-loading per generated unit of electrical energy, nuclear decommissioning, and back-end costs are assumed based on the World Nuclear Association [50]. The electricity transmission and distribution loss is assumed to be 8% according to the IEA [51].

The global economic potential of hydroelectric power generation is set constantly over time, according to Lako et al. [52], while the potential of biomass-fuel for power generation is assumed to increase with the passage of time based on Koornneef et al. [53]. Fuel prices are assumed to simply remain constant at their 2010 level [25] as the default value throughout the evaluation time periods. The apparent CO_2 emission factor of fossil fuels follows the IPCC's guidelines [54].

As for the energy system's 'inertia' constraint, decadal growth of newly installed capacity is limited to no greater than five-fold for conventional centralized power-generation options. Newly installed capacity is also assumed to be no less than half per decade for all power-generation options, except nuclear after its exit.

In the Regional (1:20 scale) model, electrical energy demand, power generation capacity, and potential of hydropower and biomass-fuel are set at 1/20th (= 5%) of the Global (1:1 scale) model for all evaluation periods. For the other parameters, the same values are set for both models.

The models are described with GAMS [55], and solved using CONOPT [56]. The source code is available from the author upon request.

4.2. Results and discussion

4.2.1. Global (1:1 scale) model

The least-cost power-generation mix calculated for the 'No nuclear exit after accident' case with the conventional modeling method, under the default parameter settings, is shown in Fig. 3. Here, the expected value of direct damage costs caused by a potential major nuclear accident are added on to the cost of nuclear

[6] Solar power generation shows the largest cost reduction, with an average rate of 2.4% per year, followed by the wind option. Though it is uncertain whether the cost-reduction trend would continue for over a half century, the assumed reduction rate is modest compared to the average rate of decline of the solar photovoltaic power-generation system price of 6% or greater per year for the period from 1998 to 2014, and to the analyst's prediction for the cost decline up to 2020 in the United States [47].

[7] The extrapolation indicates that the thermal efficiency of the gas-fueled option reaches 64.8% by 2100. This high efficiency level does not seem unattainable, in theory at least, given that a simulation study showed that a solid oxide fuel cell integrated combined cycle can potentially achieve a thermal efficiency of 67% [48].

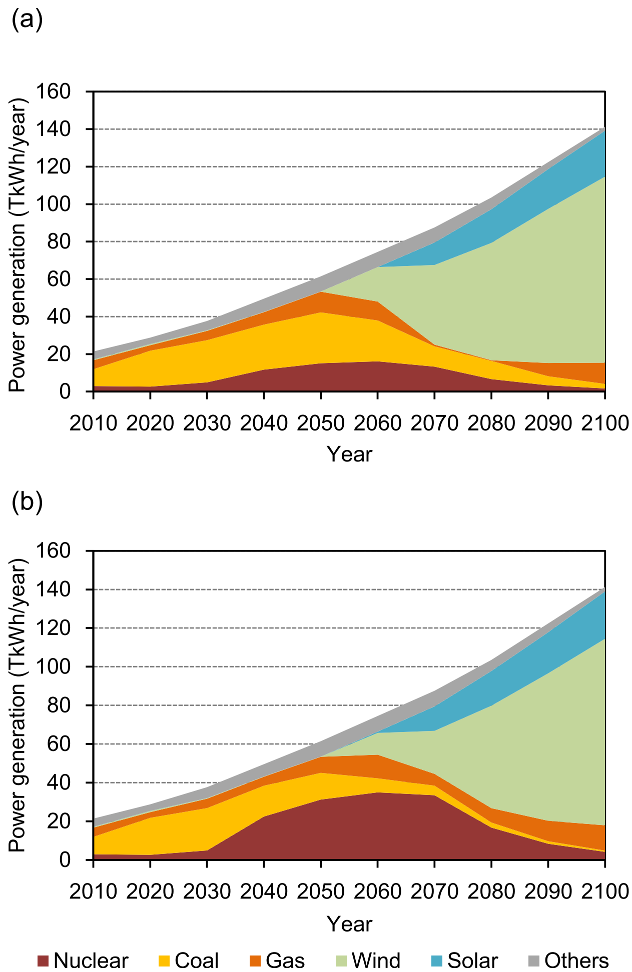

Fig. 3. Power-generation mix in the 'No nuclear exit after accident' case for the assumed frequency of a nuclear accident per generated unit of electrical energy $p_{ac} =$ (a) 1×10^{-4}, and (b) 1×10^{-5} (reactor·year)$^{-1}$ or less, using the Global model.

power generation as part of the overall power-generation cost, which is the objective function of the model.

When we assume that the value of $p_{ac} = 1\times10^{-4}$ (reactor·year)$^{-1}$ (equivalent to 1×10^{-4}/7.6 TWh^{-1}), the expected value of the accident damage costs (i.e., the add-on costs) are calculated to be 1×10^{-4}/7.6 × 150 billion USD/TWh ≅2 USD/MWh. When $p_{ac} = 1 \times 10^{-5}$ and 1×10^{-6} (reactor·year)$^{-1}$, the add-on costs become 0.2 and 0.02 USD/MWh, respectively.

In this case, under our assumptions, adding the cost of 0.2 USD/MWh or less onto the cost of nuclear power generation is too small to affect its large/small relation to the costs of other power-generation options. Therefore, the optimal power-generation mix is identical for $p_{ac} \leq 1 \times 10^{-5}$ (reactor·year)$^{-1}$ (Fig. 3(b)). For $p_{ac} = 1 \times 10^{-4}$ (reactor·year)$^{-1}$, on the other hand, the optimal power-generation share of nuclear decreases to less than half of the former assumed frequency. Nevertheless, nuclear electricity constitutes 24% of the total power supply in the middle of this century, as can be seen in Fig. 3(a). The percentage of nuclear energy declines as it gives way to wind and solar power generation, as their capital costs become competitive in the latter half of the century. These are, however, intermittent power-generation options, and so cannot be relied upon to satisfy the peak power load. Thus, with the growth of the intermittent options, the capacity of gas-fired power generation increases to ensure the power supply against shortage at all times, although this does not appear in the figures. Negative emission options with CO_2 capture are calculated to be installed not by 2100 but after that.

Fig. 4 shows the optimal mix of power generation for the 'Nuclear exit after accident' case, based on the proposed modeling. The result for the assumed frequency of a nuclear accident being

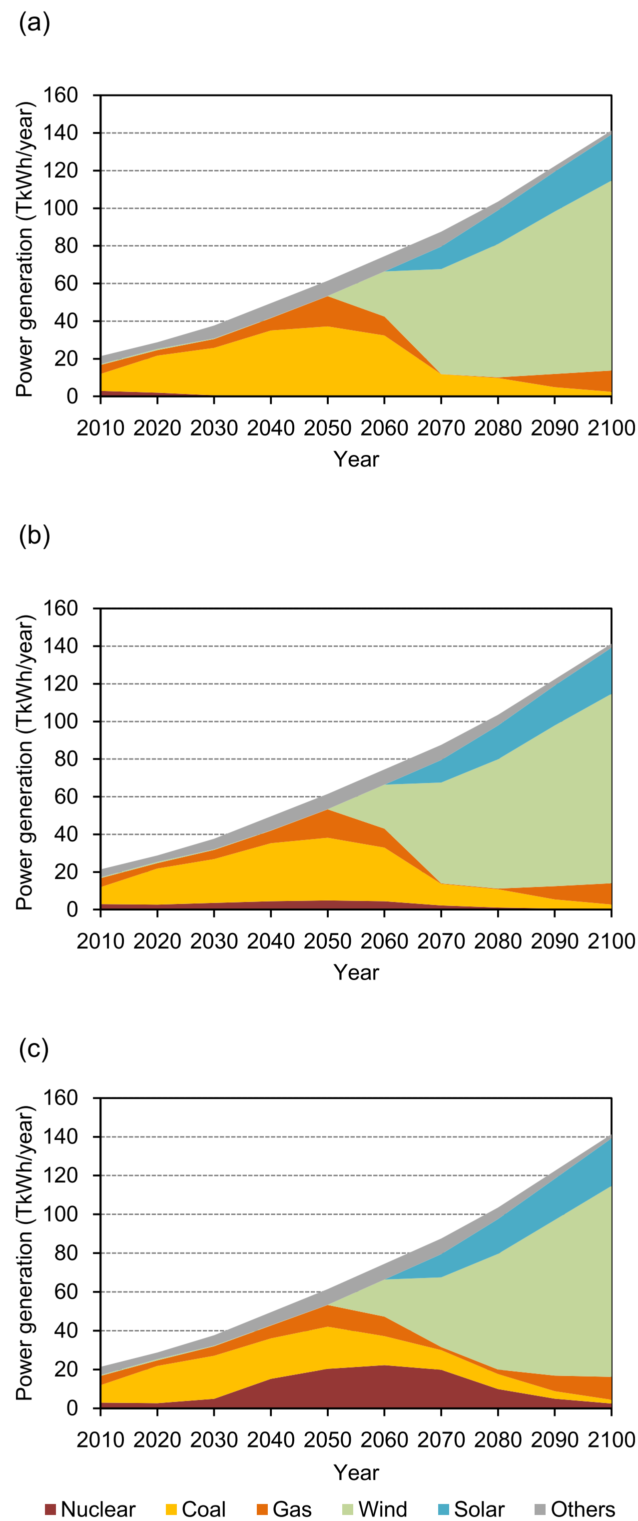

Fig. 4. Power-generation mix in the 'Nuclear exit after accident' case for $p_{ac} =$ (a) 1×10^{-4}, (b) 1×10^{-5}, and (c) 1×10^{-6} (reactor·year)$^{-1}$, using the Global model.

absolutely zero is omitted, as it is identical to the corresponding result in the former case. While the present case explicitly assumes a state of accident occurrence leading to a nuclear exit at any time period, Fig. 4(a)–(c) show the results for the state without an accident occurring until the end of this century. The (fortunate) probability of reaching this state is shown in the Appendix. The optimal power-generation share of nuclear is less than that for the 'No nuclear exit after accident' case for each assumed frequency of a nuclear accident. For $p_{ac} = 1 \times 10^{-4}$ (reactor·year)$^{-1}$, the result shows no more installation of nuclear power plants.

Obviously, the overall power-generation cost is lowest for the assumed frequency of a major nuclear accident being absolutely zero. Fig. 5 shows the increase in total discounted cost of overall power generation, including the expected cost of an accident relative to that for absolutely zero accident frequency. The figures for the 'Nuclear exit after accident' case assume no accident occurrence by 2100.

As can be seen in Fig. 5, in the 'No nuclear exit after accident' case, the power-generation cost excluding the expected cost of an accident is unvarying for $p_{ac} \leq 1 \times 10^{-5}$ (reactor·year)$^{-1}$. For a higher assumed frequency of 1×10^{-4} (reactor·year)$^{-1}$, the cost increase is 94 billion USD, equivalent to two-thirds of the direct-damage cost suffered if a major accident were to occur. The expected cost of an accident is 271 billion USD for $p_{ac} = 1 \times 10^{-4}$ (reactor·year)$^{-1}$, which is larger than the increased power-generation cost excluding the accident cost.

In contrast, in the 'Nuclear exit after accident' case the power-generation cost excluding the expected cost of an accident is calculated to be substantially larger in accordance with the smaller optimal share of nuclear shown earlier. While the expected cost of an accident is reduced by about 60% or more, the overall power-generation cost including the expected cost of an accident is larger (e.g., by 200 billion USD for $p_{ac} = 1 \times 10^{-5}$ (reactor·year)$^{-1}$) than in the former case.

4.2.2. Regional (1:20 scale) model

The optimal generated electrical energy of each power generation option calculated for the 'No nuclear exit after accident' case using the Regional model turned out to be simply 1/20th of the corresponding power generation obtained using the Global model. This is because, while the impact of a nuclear exit on the overall regional power-generation cost is inversely proportional to the scale of the region, the probability of an accident occurrence is in proportion to the amount of nuclear power generation, and it changes linearly with the scale of the region.

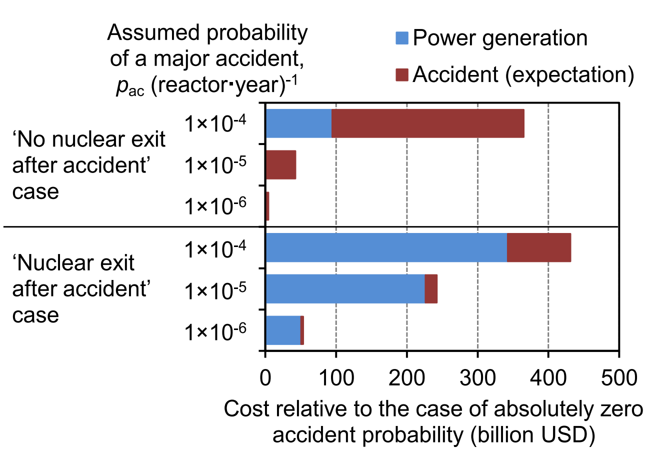

Fig. 5. Total discounted cost of overall power generation during 2010–2100, relative to the case of absolutely zero accident frequency ($p_{ac} = 0$), using the Global model.

For the 'Nuclear exit after accident' case, the above simple proportionality doesn't apply except for $p_{ac} = 0$. Fig. 6 shows the optimal intertemporal paths to a power-generation mix for this case. Comparing Fig. 6 with Fig. 4 reveals that the optimal share of nuclear in the total power supply obtained using the Regional model is larger than that using the Global model for same p_{ac}. For $p_{ac} = 1 \times 10^{-4}$

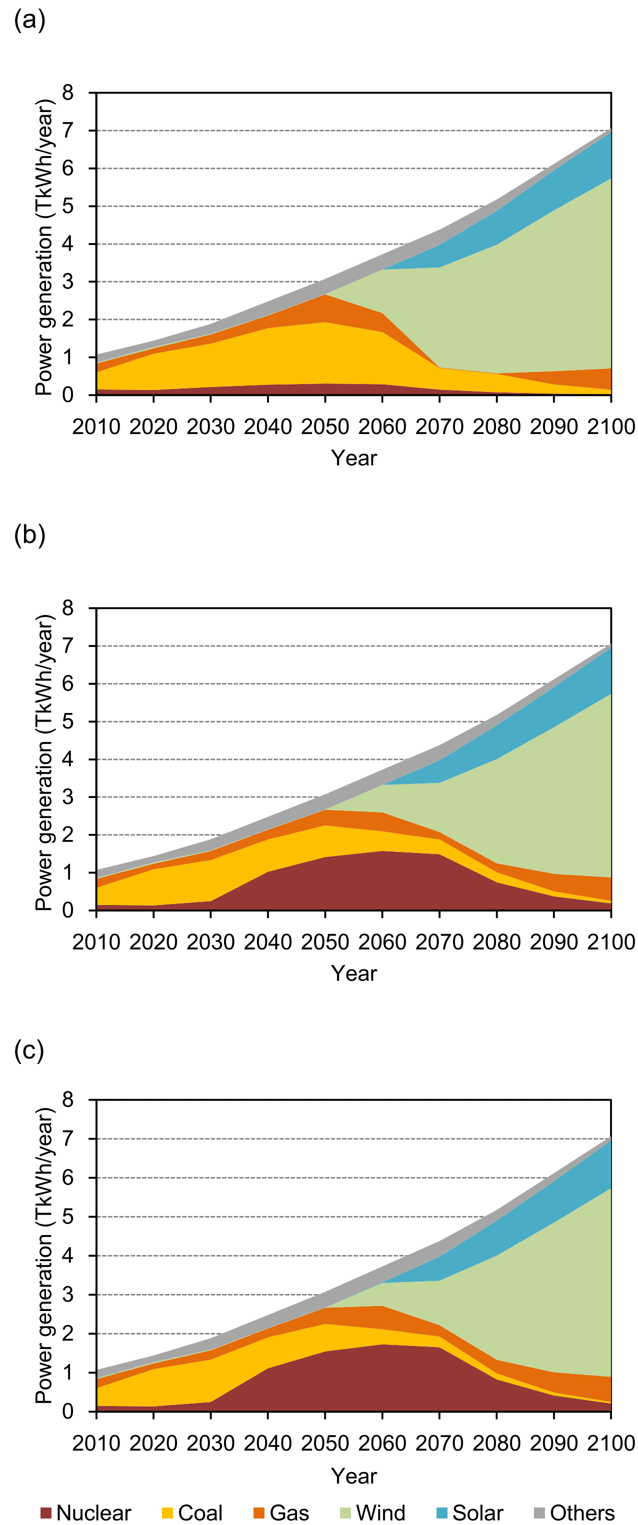

Fig. 6. Power-generation mix in the 'Nuclear exit after accident' case for $p_{ac} = $ (a) 1×10^{-4}, (b) 1×10^{-5}, and (c) 1×10^{-6} (reactor·year)$^{-1}$, using the Regional model.

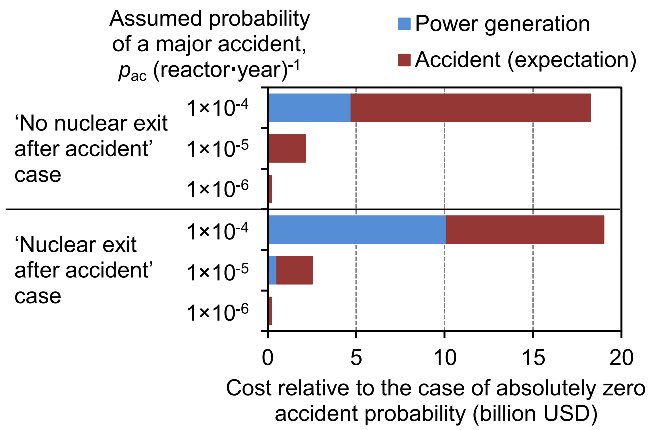

Fig. 7. Total discounted cost of overall power generation during 2010–2100, relative to the case of absolutely zero accident frequency ($p_{ac} = 0$), using the Regional model.

(reactor·year)$^{-1}$, for example, the optimal power planning suggests increasing the generated electrical energy from nuclear by a factor of 2.1 from 2010 to 2050; meanwhile, the Global model suggested phasing out nuclear power beginning immediately. This is because, for a narrower coverage of the evaluation region, the regional amount of nuclear power generation tends to be smaller, and accordingly, the cumulative probability of an accident occurring is also likely to be smaller, lowering the probability of a nuclear exit which would have adverse impacts on the overall power-generation cost.

Fig. 7 shows the increase in the total discounted cost of overall power generation, including the expected cost of an accident, relative to that for absolutely zero accident frequency in the Regional model. For the 'No nuclear exit after accident' case, the power generation costs here are simply 1/20th of those in the Global model. Comparing Fig. 7 with Fig. 5 explains how the geographical scale of a nuclear exit caused by an accident influences the optimal power-generation mix, and the corresponding power-generation cost, in the 'Nuclear exit after accident' case.

If a nuclear exit ranges over a wider scale, the exit-oriented loss becomes so large that the pressure for lowering the cumulative probability of an accident occurrence grows, which restrains the share of nuclear generation in total electrical energy supply. Accordingly, the power-generation cost excluding the expected cost of an accident increases substantially compared to the 'No nuclear exit after accident' case. While the expected cost of an accident decreases, this decrease doesn't come close to covering the above cost increase if the nuclear exit ranges over the whole world. Therefore, even when p_{ac} is reduced to 1×10^{-6} (reactor·year)$^{-1}$, it would be reasonable to lower the share of nuclear and accept a higher overall power-generation cost in the 'Nuclear exit after accident' case compared to the 'No nuclear exit after accident' case.

For a narrower scale of nuclear exit, on the other hand, the optimal power-generation mix and the power-generation cost in the 'Nuclear exit after accident' case gets closer to the results for the 'No nuclear exit after accident' case, as a higher risk of nuclear exit can be tolerated. Consequently, when p_{ac} is reduced to 1×10^{-6} (reactor·year)$^{-1}$, the impact of a nuclear accident leading to an exit or not on the results becomes negligible if the exit ranges only over 1/20th of the globe.

5. Selected sensitivity analysis

While we have presented a demonstration of the model under simple assumptions, these assumed values have uncertainties; changes in any parameter values should affect the quantitative results calculated using the model. Selecting three crucial parameters, i.e., the price of fossil fuel, the direct damage cost of a major nuclear accident, and the demand for electric power energy, the following analysis examines the cases in which the assumed values for these parameters are set at levels different from the default settings.

5.1. Cases assumed

The following three variations of the parameter settings are considered for the sensitivity analysis.

- Higher fuel price: the international prices of coal, gas, and oil are assumed to rise in line with the Current Policies Scenario shown in the WEO [42] by 2030; linearly extrapolating from these 20-year price developments, the prices of coal, gas, and oil are assumed to reach 1.5, 2.8, and 2.9 times by 2100 as much as those in 2010, respectively. As no specific assumption is presented for the price of uranium in the WEO [42], the future uranium prices are set in conjunction with the assumed coal prices, adopting a statistically-derived ratio of the change in the uranium price to that in the coal price.[8] Accordingly, the uranium price is assumed to grow by 62% by 2100 relative to the 2010 level.
- Higher damage cost: the damage cost of a major nuclear accident, δ_{ac}, is assumed to be 1.5 trillion USD, 10 times as much as the default setting assumed earlier based on the EC [13], taking into consideration that Rabl and Rabl obtained a high estimate of the damage cost, namely 1.39 trillion Euros [17].
- Lower electricity demand: the global electrical energy demand under the Blue Map scenario, which assumes advanced energy savings, shown in the IEA's Energy Technology Perspective 2010 [51] is adopted for the year 2050. The demands for the other time periods are set based on the energy-saving rate of this lower assumption relative to the default value in 2050. The assumed lower global demand for 2100 is 71.3 TkWh, 45% lower than the default value for the same time period.

5.2. Results

Fig. 8 shows the optimal mix of power generation in 2060 for the three variations of the parameter settings calculated by the proposed modeling, i.e., for the 'Nuclear exit after accident' case. The results based on the default parameter settings are also included for comparison. Focusing on the middle of this century, when the optimal power generated by nuclear approaches its peak under the default settings for the lowest assumed frequencies of a nuclear accident, clarifies the sensitivity of the optimal mix to the parametric variation.

Fig. 8(a) shows the results obtained using the Global model. Assuming the higher fuel prices excludes the gas power generation option from the optimal mix due to the surge in gas prices, which results in more dependency on solar and wind power generation. Compared to the results for the default settings, assuming the frequency of a nuclear accident p_{ac} to be as low as 1×10^{-6} (reactor·year)$^{-1}$ yields a slighter decrease in the optimal share of nuclear in the total power supply relative to that for an accident frequency of absolutely zero. This reflects the modest rise in the price of uranium relative to fossil-fuels in the case of higher fuel

[8] Based on the insight that uranium prices were correlated with coal prices [57], a simple linear regression analysis was applied for the annual average international uranium prices [58] and coal price indices [59] over the past 21 years. This analysis derived an ordinary least squares estimation of the coefficient of the change in uranium price per unit change in coal price with the adjusted R^2 value of 0.926.

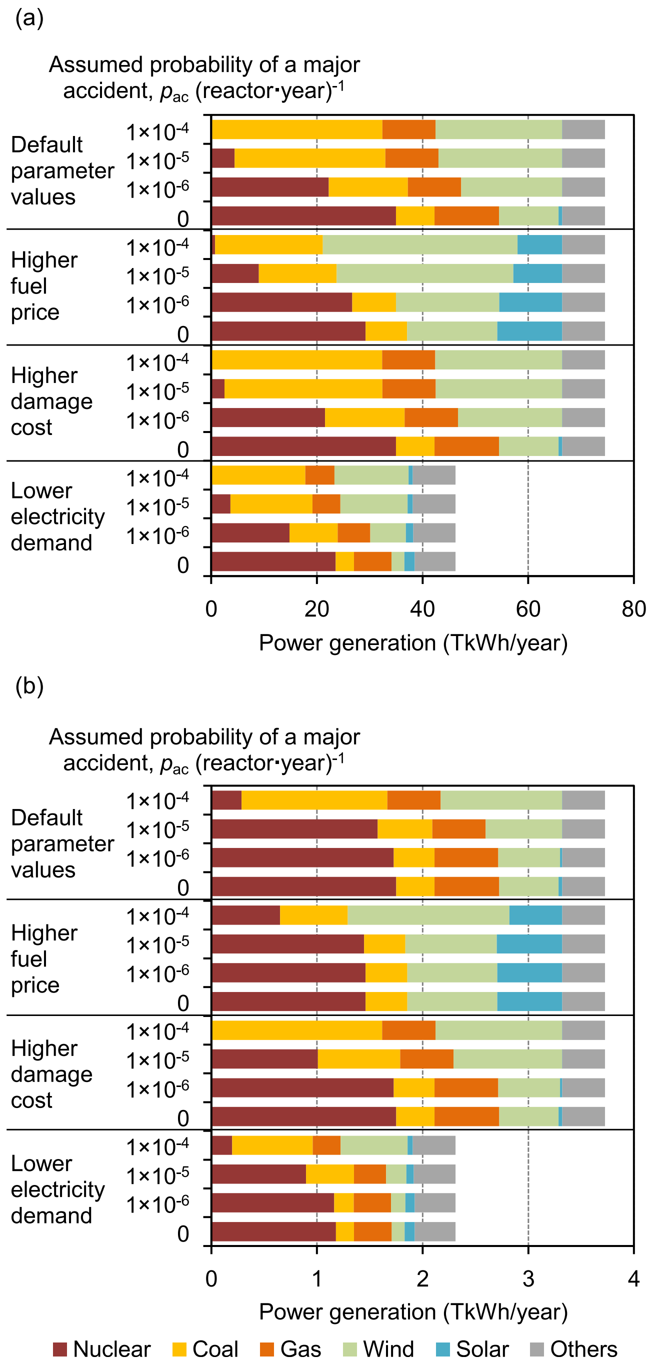

Fig. 8. Power-generation mix in 2060 in the 'Nuclear exit after accident' case for the assumed variations of the parameter settings, using (a) the Global and (b) Regional models.

prices. The assumed large-scale damage cost of an accident δ_{ac} has only a small impact on the results because the scale of δ_{ac} accounts for a relatively small percentage of the overall global power-generation cost. For the assumed lower electricity demand, the power energy generated from each power generation option is saved generally in accordance with the rate at which the total electricity use is reduced.

The results obtained using the Regional model are shown in Fig. 8(b). The tendency observed earlier for the default assumptions, namely that depending more on nuclear is optimal even for higher values of p_{ac} compared to the results of the Global model, also generally holds for these three variations of the parameter settings. Examining more closely, the value of p_{ac} acceptable for keeping the optimal nuclear dependency from being curtailed is relaxed to 1×10^{-5} (reactor·year)$^{-1}$ under the assumption of higher fuel prices, which allow nuclear power generation to be more cost-advantageous than fossil-fired options. On the other hand, as a large δ_{ac} weighs relatively heavily on a narrower evaluation region under the higher damage cost assumption, the optimal nuclear dependency is considerably decreased when the value of p_{ac} is as large as 1×10^{-5} (reactor·year)$^{-1}$ from the results for lesser values of p_{ac}, whereas this decrease is modest for the same p_{ac} under the default settings. The influence of assuming a lower electricity demand on the optimal share of nuclear is virtually unnoticeable.

6. Conclusions

In this paper, a stochastic modeling method for power-generation planning was proposed so as to explicitly take into account two types of cost caused by a potential major nuclear accident. The first is the cost of damage directly caused by the accident, while the second cost is the result of changes in the power-generation mix due to a nuclear exit prompted by lowered public acceptance of nuclear power.

According to the demonstration of the proposed model, cost-optimal power-generation planning under the possibility of a nuclear exit triggered by a nuclear accident suggests lessening nuclear dependency in order to mitigate the potentially large overall power-generation cost increase of a change in the power-generation structure in the case of nuclear exit—if we assume a larger frequency of a nuclear accident per generated unit of electrical energy. The nuclear exit-originated increase in the overall power-generation cost could be larger than the direct-damage costs of a nuclear accident. Conversely, the above result could be interpreted as suggesting that lowering the frequency of a major accident per generated unit of electrical energy by improving the safety of nuclear power plants and thus preventing a nuclear exit brings benefits that greatly exceed the conventionally perceived effect of reducing an accident's direct damage. Were the frequency of a major accident, p_{ac}, improved to 1×10^{-6} (reactor·year)$^{-1}$ or less, the optimal planning of future electric power supply would be uninfluenced by whether the accident causes the nuclear exit if the geographical scale of the exit is limited to 1/20th of the world.

A sensitivity analysis for a selected set of critical assumptions implied that, when the prices of gas and oil were assumed to increase relative to the price of nuclear fuel, the optimal dependency of nuclear in the total power supply tended to remain the same when the frequency of accidents causing a nuclear exit was higher. For example, in the case of higher fossil-fuel prices, the optimal power-generation mix could be unaffected even for values of p_{ac} as high as 1×10^{-5} (reactor·year)$^{-1}$ if the geographical scale of the nuclear exit after an accident was 1/20th of the world. Assuming a higher direct damage cost of an accident or a lower growth of electrical energy demand had only a slight impact on the optimal power-generation mix.

To recapitulate, the significance of this study can be summarized as follows. (1) The study proposed a precautionary principle considering not only the direct damage (the first type of loss) but also the possibility of a nuclear exit (the second type of loss) caused by another major nuclear accident in the future, and took a first step to applying the principle in the optimal expansion planning of power generation. (2) As a specific modeling methodology for this application, the study presented a mathematical formulation to develop a practically solvable stochastic programming model in which nuclear power generation could be forced to stop at any time with the probability of an accident determined endogenously in connection with the energy generated from nuclear. (3) Through a first demonstration of the proposed modeling, this study evaluated the impact of considering the second type of loss on future optimal power-generation planning, especially on the optimal share of nuclear; it also gave insight into the required target frequency of a major nuclear accident per reactor·year for the optimal nuclear dependency to be uninfluenced even by considering the second type of loss; further it investigated the robustness of those results with respect to changes in the critical assumptions.

It should be noted that extending the model to incorporate more realistic conditions would either increase or decrease the estimated impact of the nuclear exit on the increase in the overall power-generation cost. For example, applying risk-averse decision criteria, instead of the risk-neutral criterion on which the expected cost-minimization adopted in this study is based, would revise up the estimated impact so that the optimal generated electrical energy from nuclear would be scaled down. Indeed, Eeckhoudt et al. [60] argue that the accident-induced direct damage cost per generated unit of electrical energy should be regarded as twenty times the conventional expected external cost of an accident, assuming the coefficient of relative risk aversion as two.

On the other hand, the estimated impact could be revised down assuming a temporally limited nuclear exit and/or a gradual phase-out rather than the permanent exit assumed in this study. This would also apply if a nuclear exit were assumed to accelerate R&D, and consequently, produce cost reduction of power-generation technologies other than nuclear.

Of course, assumptions of energy demands and fuel prices are more basic factors influencing the results. While these are treated simply as exogenous parameters in this study, in reality they would influence each other and would depend on other economic factors. Moreover, the security of the energy supply is also an important factor that must be taken into account, and which would be especially crucial in regional or local evaluations.

This study went no further than a first attempt to endogenize the probability of a nuclear exit led by a nuclear accident in a power-generation mix model. Revisions and extensions of the proposed model are expected for application to various regional power-generation models.

Acknowledgments

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Appendix. Calculated cumulative probability of no accident occurrence

Figure A.1 shows the cumulative probabilities of the nonoccurrence of a nuclear accident (i.e., the variable $P_n(t)$ that appears in Section 3.2 of the main text), calculated with the Global and Regional models, respectively, under the assumptions in this study. The values mean the probability that (fortunately) no major accident occurs by certain time periods.

In general, the calculated values of $P_n(t)$ decrease with a larger assumed value of the frequency of an accident per generated unit of electrical energy from nuclear (i.e., the parameter p_{ac}), and also with the passage of time. The values of $P_n(t)$ tend to be smaller in the 'No nuclear exit after accident' case, as in this case the optimal amount of nuclear power generation is greater, compared to those in the 'Nuclear exit after accident' case.

Comparing the calculated results using the Global model with those using the Regional model reveals that an accident occurrence is less likely (i.e., the values of $P_n(t)$ are larger) for the latter model, as their geographical scope is narrower, and thus the absolute amount of nuclear power generation is smaller. It can also be seen that, for the Regional model, the values of $P_n(t)$ computed in the 'Nuclear exit after accident' case get closer to those in the 'No nuclear exit after accident' case as a smaller value of p_{ac} is assumed; there is no difference in the results between the two cases for $p_{ac} = 1\times10^{-6}$ (reactor·year)$^{-1}$.

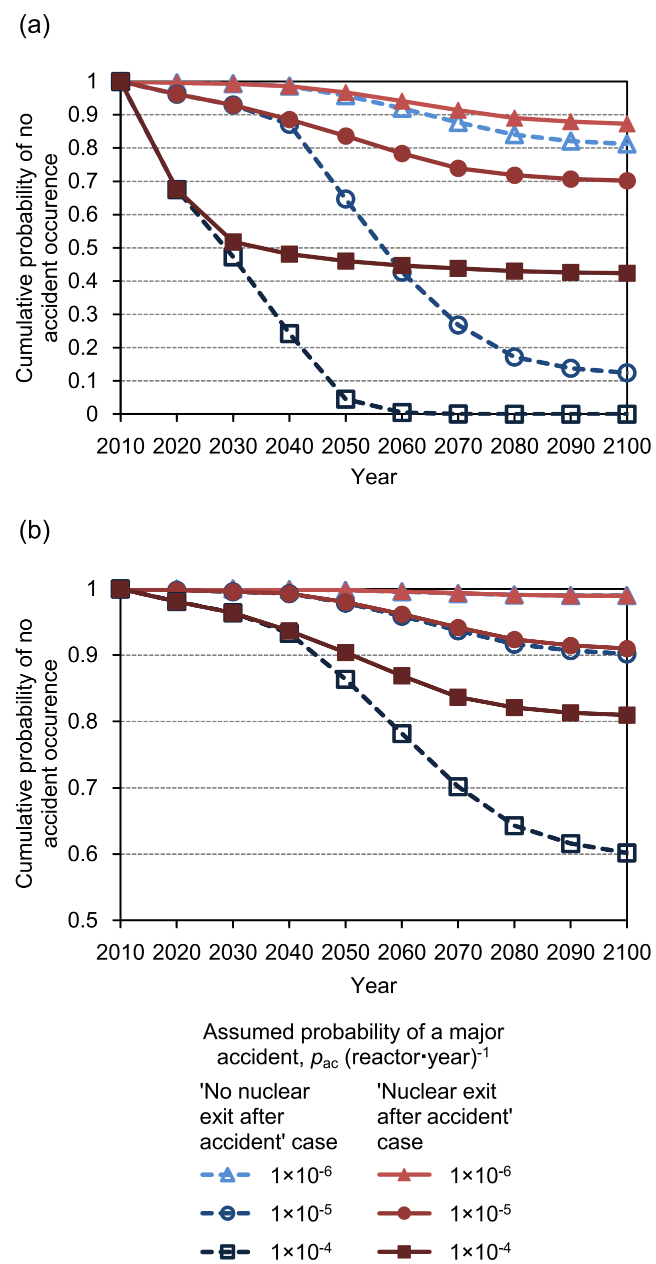

Fig. A.1. Cumulative probability of no nuclear accident, when a nuclear accident does not to occur by 2100, using (a) the Global model, and (b) the Regional model.

References

[1] Van der Zwaan B. The role of nuclear power in mitigating emissions from electricity generation. Energy Strateg Rev 2013;1(4):296–301. http://dx.doi.org/10.1016/j.esr.2012.12.008.

[2] Tokimatsu K, Kosugi T, Asami T, Williams E, Kaya Y. Evaluation of lifecycle CO_2 emissions from the Japanese electric power sector in the 21st century under various nuclear scenarios. Energy Policy 2006;34(7):833–52. http://dx.doi.org/10.1016/j.enpol.2004.08.011.

[3] Echavarri LE. The future of nuclear power. Energy Strategy Rev 2013;1(4):221–2. http://dx.doi.org/10.1016/j.esr.2012.10.001.

[4] Agency for Natural Resources and Energy. On recent situation involving energy issues, material distributed at the 15th meeting of the Strategic Policy Subcommittee of the Advisory Committee for Natural Resources and Energy, 19 November 2014 (in Japanese). 2014. http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/015/pdf/015_007.pdf [accessed 14.01.15].

[5] Tokyo Electric Power Company. http://www.tepco.co.jp/en/comp/images/jisseki-e.pdf; 2015 [accessed 30.11.15].

[6] Jorant C. The implications of Fukushima: the European perspective. Bull Atomic Sci 2011;67(4):14–7. http://dx.doi.org/10.1177/0096340211414842.

[7] Siegrist M, Sütterlin B, Keller C. Why have some people changed their attitudes toward nuclear power after the accident in Fukushima? Energy Policy 2014;69:356–63. http://dx.doi.org/10.1016/j.enpol.2014.02.026.

[8] Hayashi M, Hughes L. The Fukushima nuclear accident and its effect on global energy security. Energy Policy 2013;59:102–11. http://dx.doi.org/10.1016/j.enpol.2012.11.046.

[9] Csereklyei Z. Measuring the impact of nuclear accidents on energy policy. Ecol Econ 2014;99:121–9. http://dx.doi.org/10.1016/j.ecolecon.2014.01.010.

[10] Joskow PL, Parsons JE. The economic future of nuclear power. Daedalus 2009;138(4):45–59. http://dx.doi.org/10.1162/daed.2009.138.4.45.

[11] Joskow PL, Parsons JE. The future of nuclear power after Fukushima. Econ Energy Environ Policy 2012;1(2):99–114. http://dx.doi.org/10.5547/2160-5890.1.2.7.

[12] Pedraza JM. World major nuclear accidents and their negative impact in the environment, human health and public opinion. Int J Energy Environ Econ 2013;21(2):1–23. https://www.researchgate.net/publication/248399880_World_major_nuclear_accidents_and_their_negative_impact_in_the_environment_human_health_and_public_opinion [accessed 19.10.15].

[13] The European Commission (EC). ExternE: externalities of energy, Vol. 5: Nuclear. Project report EUR 16524. Luxembourg: Office for Official Publications of the European Communities; 1995.

[14] Sheldon S, Hadian S, Zik O. Beyond carbon: quantifying environmental externalities as energy for hydroelectric and nuclear power. Energy 2015;84:36–44. http://dx.doi.org/10.1016/j.energy.2015.01.116.

[15] Sovacool BK, Kryman M, Laine E. Profiling technological failure and disaster in the energy sector: a comparative analysis of historical energy accidents. Energy 2015;90(2):2016–27. http://dx.doi.org/10.1016/j.energy.2015.07.043.

[16] Silva K, Ishiwatari Y, Takahara S. Cost per severe accident as an index for severe accident consequence assessment and its applications. Reliab Eng Syst Saf 2014;123:110–22. http://dx.doi.org/10.1016/j.ress.2013.11.004.

[17] Rabl A, Rabl VA. External costs of nuclear: greater or less than the alternatives? Energy Policy 2013;57:575–84. http://dx.doi.org/10.1016/j.enpol.2013.02.028.

[18] Hughes L. The effects of event occurrence and duration on resilience and adaptation in energy systems. Energy 2015;84:443–54. http://dx.doi.org/10.1016/j.energy.2015.03.010.

[19] Rafaj P, Kypreos S. Internalisation of external cost in the power generation sector: analysis with global multi-regional MARKAL model. Energy Policy 2007;35:828–43. http://dx.doi.org/10.1016/j.enpol.2006.03.003.

[20] de-Llano Paz F, Antelo SI, Silvosa AC, Soares I. The technological and environmental efficiency of the EU-27 power mix: an evaluation based on MPT. Energy 2014;69:67–81. http://dx.doi.org/10.1016/j.energy.2014.02.036.

[21] Kosugi T, Tokimatsu K, Kurosawa A, Itsubo N, Yagita H, Sakagami M. Internalization of the external costs of global environmental damage in an integrated assessment model. Energy Policy 2009;37(7):2664–78. http://dx.doi.org/10.1016/j.enpol.2009.02.039.

[22] Zheng Y, Hu Z, Wang J, Wen Q. IRSP (integrated resource strategic planning) with interconnected smart grids in integrating renewable energy and implementing DSM (demand side management) in China. Energy 2014;76:863–74. http://dx.doi.org/10.1016/j.energy.2014.08.087.

[23] Yuan J, Xu Y, Kang J, Zhang X, Hu Z. Nonlinear integrated resource strategic planning model and case study in China's power sector planning. Energy 2014;67:27–40. http://dx.doi.org/10.1016/j.energy.2013.12.054.

[24] Hong S, Bradshaw CJA, Brook BW. Evaluating options for sustainable energy mixes in South Korea using scenario analysis. Energy 2013;52:237–44. http://dx.doi.org/10.1016/j.energy.2013.02.010.

[25] Seddighi AH, Ahmadi-Javid A. Integrated multiperiod power generation and transmission expansion planning with sustainability aspects in a stochastic environment. Energy 2015;86:9–18. http://dx.doi.org/10.1016/j.energy.2015.02.047.

[26] Rogner M, Riahi K. Future nuclear perspectives based on MESSAGE integrated assessment modeling. Energy Strateg Rev 2013;1(4):223–32. http://dx.doi.org/10.1016/j.esr.2013.02.006.

[27] Duscha V, Schumacher K, Schleich J, Buisson P. Costs of meeting international climate targets without nuclear power. Clim Policy 2014;14(3):327–52. http://dx.doi.org/10.1080/14693062.2014.852018.

[28] Bauer N, Brecha RJ, Luderer G. Economics of nuclear power and climate change mitigation policies. Proc Natl Acad Sci U. S. A 2012;109(42):16805–10. http://dx.doi.org/10.1073/pnas.1201264109.

[29] Nakata T. Analysis of the impacts of nuclear phase-out on energy systems in Japan. Energy 2002;27(4):363–77. http://dx.doi.org/10.1016/S0360-5442(01)00090-1.

[30] Su X, Zhou W, Nakagami K. Study on reducing nuclear dependence in post-Fukushima Japan. Policy Sci 2013;20(2):55–65. http://r-cube.ritsumei.ac.jp/bitstream/10367/4683/1/ps20_2su.pdf [accessed 14.01.15].

[31] Zhang Q, Mclellan BC, Tezuka T, Ishihara KN. Economic and environmental analysis of power generation expansion in Japan considering Fukushima nuclear accident using a multi-objective optimization model. Energy 2012;44(1):986–95. http://dx.doi.org/10.1016/j.energy.2012.04.051.

[32] Jacoby HD, Paltsev S. Nuclear exit, the US energy mix, and carbon dioxide emissions. Bull Atomic Sci 2013;69(2):34–43. http://dx.doi.org/10.1177/0096340213478553.

[33] Bruninx K, Madzharov D, Delarue E, D'haeseleer W. Impact of the German nuclear phase-out on Europe's electricity generation—a comprehensive study. Energy Policy 2013;60:251–61. http://dx.doi.org/10.1016/j.enpol.2013.05.026.

[34] Kannan R, Turton H. Cost of ad-hoc nuclear policy uncertainties in the evolution of the Swiss electricity system. Energy Policy 2012;50:391–406. http://dx.doi.org/10.1016/j.enpol.2012.07.035.

[35] De Cian E, Carrara S, Tavoni M. Innovation benefits from nuclear phase-out: can they compensate the costs? Clim Change 2014;123(3–4):637–50. http://dx.doi.org/10.1007/s10584-013-0870-9.

[36] Komiyama R, Fujii Y. Assessment of Japan's optimal power generation mix considering massive deployment of variable renewable power generation. Electr Eng Jpn 2013;185(2):1–11. http://dx.doi.org/10.1002/eej.22470.

[37] Kosugi T. Fail-safe solar radiation management geoengineering. Mitig Adapt Strateg Glob Change 2013;18(8):1141–66. http://dx.doi.org/10.1007/s11027-012-9414-2.

[38] The Nuclear Regulatory Commission (NRC). Severe accident risks—an assessment for five U.S. Nuclear power plants. NUREG 1150. Rockville, MD: NRC; 1990. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1150/ [accessed 29.03.13].

[39] Gaertner J, Canavan K, True D. Safety and operational benefits of risk-informed initiatives. An EPRI White Paper. CA: Electric Power Research Institute; 2008. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001016308 [accessed 29.03.13].

[40] Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, de la Vega Navarro A, Edmonds J, et al. Energy systems. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.

[41] The International Energy Agency (IEA). World energy outlook 2012. Paris: OECD/IEA; 2012. http://dx.doi.org/10.1787/weo-2012-en.

[42] The International Energy Agency (IEA). World energy outlook 2013. Paris: OECD/IEA; 2013. http://dx.doi.org/10.1787/weo-2013-en.

[43] Nakićenović N, Swart R, editors. Special report on emissions scenarios. Cambridge, UK: Cambridge University Press; 2000.

[44] Select Committee on Economics Affairs, the United Kingdom Parliament House of Lords. Memorandum by Professor Richard S J Tol. Hamburg: Vrije and Carnegie Mellon Universities; 2005. http://www.publications.parliament.uk/pa/ld200506/ldselect/ldeconaf/12/5020107.htm [accessed 19.10.15].

[45] Japan Electric Power Information Center (JEPIC). Overseas electric power industry statistics 2012. Tokyo: JEPIC; 2012.

[46] The International Energy Agency (IEA). Assumed investment costs, operation and maintenance costs and efficiencies in the IEA World Energy Outlook 2011. Paris: OECD/IEA; 2011. http://www.iea.org/media/weowebsite/energymodel/WEO_2011_PG_Assumptions_450_Scenario.xls [accessed 14.03.13].

[47] Barbose G, Darghouth N. Tracking the Sun VIII: an historical summary of the installed price of photovoltaics in the United States from 1998 to 2014. Berkeley, CA: Lawrence Berkeley National Laboratory; 2015. https://emp.lbl.gov/sites/all/files/lbnl-188238_1.pdf [accessed 21.10.15].

[48] Gogoi TK, Sarmah P, Nath DD. Energy and exergy based performance analyses of a solid oxide fuel cell integrated combined cycle power plant. Energy Convers Manag 2014;86:507–19. http://dx.doi.org/10.1016/j.enconman.2014.06.006.

[49] IEA, the Nuclear Energy Agency (NEA). Projected costs of generating electricity 2015. Paris: OECD/IEA-NEA; 2015. http://dx.doi.org/10.1787/cost_electricity-2015-en.

[50] The World Nuclear Association (WNA). The economics of nuclear power (updated March 2013). London: WNA; 2013. http://www.world-nuclear.org/info/Economic-Aspects/Economics-of-Nuclear-Power/ [accessed 29.03.13].

[51] IEA. Energy technology perspectives 2010. Paris: OECD/IEA; 2009. http://dx.doi.org/10.1787/energy_tech-2010-en.

[52] Lako P, Eder H, De Noord M, Reisinger H. Hydropower development with a focus on Asia and Western Europe. ECN-C-03–027. Petten: ECN/Verbundplan; 2003. http://www.ecn.nl/docs/library/report/2003/c03027.pdf [accessed 02.06.13].

[53] Koornneef J, Van Breevoort P, Hamelinck C, Hendriks C, Hoogwijk M, Koop K, et al. Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. Int J Greenh Gas Control 2012;11:117–32. http://dx.doi.org/10.1016/j.ijggc.2012.07.027.
[54] The Intergovenmental Panel on Climate Change (IPCC). In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. 2006 IPCC guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Tokyo: The Institute for Global Environmental Strategies; 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ [accessed 29.03.13].
[55] Brooke A, Kendrick D, Meeraus A. GAMS: a user's guide, release 2.25. San Francisco: The Scientific Press; 1992.
[56] Drud AS. CONOPT: a large-scale GRG code. ORSA J Comput 1994;6(2):207–16.
[57] Amavilah VHS. The influence of oil and coal prices on the world uranium demand. OPEC Rev 1994;18(4):489–508. http://dx.doi.org/10.1111/j.1468-0076.1994.tb00514.x.
[58] The United States Energy Information Administration. Uranium marketing annual report. 2015. http://www.eia.gov/uranium/marketing/html/summarytable1b.cfm [accessed 19.10.15].
[59] IEA. Energy prices and taxes, 3rd Quarter 2015. Paris: OECD/IEA; 2015. http://dx.doi.org/10.1787/energy_tax-v2015-3-en.
[60] Eeckhoudt L, Schieber C, Schneider T. Risk aversion and the external cost of a nuclear accident. J Environ Manag 2000;58(2):109–17. http://dx.doi.org/10.1006/jema.1999.0314.